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Three-dimensional Curvature Contrast–Geometric or Brightness Illusion?

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Simultaneous contrast effects have been found across a wide range of visual dimensions. We describe a simultaneous contrast effect—three-dimensional curvature contrast—in which the apparent curvature of a surface defined by shading and texture information is influenced by the curvature of a surrounding surface. The effect is strong and easily measurable. We asked whether the effect depends upon the presence of contrast at the level of the internal representation of surface curvature or whether it could be better explained in terms of local changes in the apparent brightness of regions within the test patches induced by luminance transitions at the borders. The experimental results suggest that, while these luminance-contrast-induced effects do contribute to the observed changes in perceived curvature, there are additional influences. In particular changes in perceived curvature induced by a pattern of curved patches were eliminated or considerably weakened when the inducing pattern was transformed into a photographic negative, a procedure which disrupts the apparent three-dimensional structure of the surface patches without changing their brightness contrast. This suggests a component of the illusion involves comparisons at the level of representation of surface curvature. The observation that three-dimensional curvature contrast persists when the inducing surfaces are spatially separate from the test surface suggests that shape perception involves global, as well as local, operations. Copyright © 1996 Elsevier Science Ltd.

Shape from shading   Simultaneous contrast   Depth processing   Three-dimensional curvature contrast

INTRODUCTION

Simultaneous contrast effects have been reported for an ever increasing range of visual stimulus properties, such as brightness, colour, spatial frequency of gratings, two-dimensional line curvature, pattern contrast, motion and depth. Two identical grey patches differ in their apparent brightness when one is embedded in a darker surround and the other is set in a lighter surround (Ratliff, 1965). Similarly, colour contrast can be demonstrated by setting one of the two grey patches against a red background and the other against a green background. Under these viewing conditions the former patch will take on a greenish hue while the latter will have an apparent reddish hue (Kinney, 1962). Gibson (1933) described a two-dimensional curvature contrast effect. In this effect a straight line segment appears slightly curved when viewed against a background of curved lines which have the same global orientation as the straight line segment. The induced curvature is opposite in polarity to the background lines. Simultaneous contrast effects have been shown for two-dimensional sine gratings. Klein *et al.* (1974) reported that the apparent frequency of a grating is shifted when the grating is surrounded by a second grating of a different frequency, and that the direction of shift is dependent on whether the frequency of the surround grating is higher or lower than the central grating. Such shifts in apparent spatial frequency are similar to those found in spatial frequency adaptation experiments (Blakemore & Sutton, 1969). When the central and surround gratings differ only in their contrast, the apparent contrast of the central grating can be shifted by varying the contrast of the surround (Cannon & Fullenkamp, 1993). This so called *contrast contrast* effect has also been demonstrated for a number of grey level textures (Chubb *et al.*, 1989).

A number of authors have reported simultaneous depth contrast effects for stimuli defined by both stereoscopic (Graham & Rogers, 1982a; Kumar & Glasner, 1991; Pastore, 1964) and motion parallax information (Graham & Rogers, 1982a). Pastore (1964) presented observers with two horizontal lines of equal length. When lines such as these are fused stereoscopically, observers typically report seeing a line lying perpendicular to the line of sight. When a pair of dots were placed at either end of the two lines, and configured such that when fused they appeared to lie along a tilted plane, the line was

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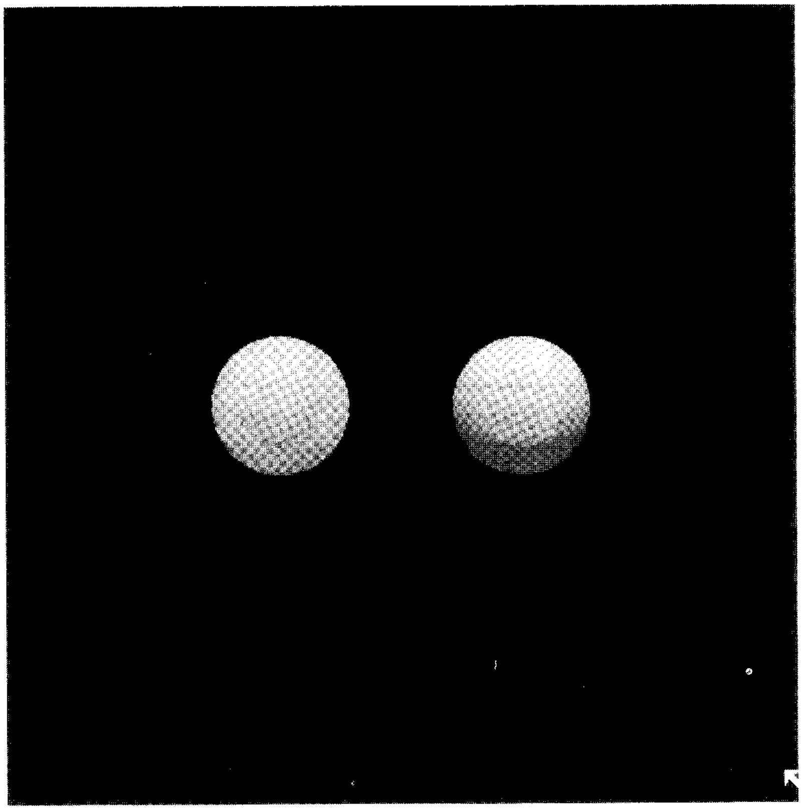

FIGURE 1. A demonstration of three-dimensional curvature contrast. The image is composed of two background spheres viewed through two circular apertures of identical diameter. Superimposed on each of the two spheres is a spherical surface patch whose curvature is equal to the mean curvature of the background spheres. The left and right background spheres have curvatures of 0.29 and 0.67 cm^{-1} (or radii of 3.5 and 1.5 cm), respectively. Although the central surface patches are identical, the left patch clearly appears the more curved of the two.

perceived as tilting in space in the direction opposite to the depth effects of the dots.

Graham and Rogers (1982) demonstrated simultaneous depth contrast effects with stimuli defined by either stereopsis or motion parallax. In their experiments subjects were presented with a horizontal central bar, lying in the fronto-parallel plane, with two flanking surfaces above and below, which were slanted out of the fronto-parallel plane. Subjects reported that the central bar appeared to slope in the opposite direction to the flanking surfaces; when half the central bar was flanked by a surface slanting forward and the other half was flanked by a surface slanting backward, the central bar appeared twisted along its length. Graham and Rogers (1982b) also report that motion parallax information can be utilized to null binocular depth aftereffects, and that binocular information can be used to null motion parallax depth aftereffects, showing that interactions occur between the two systems.

The effects reported by Graham and Rogers were found when the test surfaces were adjacent to the inducing surfaces. Kumar and Glaser (1991) have shown that stereoscopically viewed inducing and test surfaces need not be adjacent for depth contrast effects to occur. They reported that objects positioned as far as 25 deg from the point of fixation can influence the perceived differences in the depths of stimuli near fixation. Most reports of simultaneous depth contrast have used stimuli containing either motion or stereoscopic information. Here we report a depth contrast effect for stimuli defined by pictorial cues, which we refer to as three-dimensional curvature contrast (Curran & Johnston, 1994c).

Three-dimensional curvature contrast describes how two spherical surface patches, depicted by shading and texture cues and of identical curvature, appear strikingly dissimilar in their curvature when they are presented with one of the patches superimposed on a more curved background and the other on a less curved background. The effect is demonstrated in Fig. 1. The figure depicts a pair of spheres viewed through circular apertures. The sphere on the left is less curved than the sphere on the right. Superimposed on each of the spheres is a spherical surface patch whose curvature is equal to the mean curvature of the background spheres. Although the central surface patches are identical in their geometry, and their rendered images are identical in their pictorial content, the one on the left clearly appears more curved than the surface patch on the right. Thus the apparent curvature of a spherical surface is enhanced when it is set against a less-curved background surface, and is diminished when set against a more-curved background surface.

The experiments reported in this paper were designed with three goals in mind:

firstly, to quantify three-dimensional curvature contrast;

secondly, to identify what stimulus factors influence this phenomenon; and

thirdly, to test whether the effect persists when the inducing surface is spatially separate from the test surface.

The answer to the latter question is important in so far as it has some bearing on the question of whether shape-from-shading and shape-from-texture are local operations. The presence of induced effects in situations where inducing and test surfaces are spatially separated tends to imply the analysis of global information.

The results of Experiment 1 demonstrate that three-dimensional curvature contrast is a strong and easily measurable effect. Experiments two and three investigate whether the effect can be explained on the basis of changes of brightness within the test patches induced by local discontinuities in image intensity at the boundaries of the central patches. This is apparent in Fig. 1. Consider the effects of changing the curvature of a background sphere on the brightness differences at the boundary of the central patch. For spherical objects a change in curvature results in a simple expansion or contraction of the objects. In the case of a surface patch on a less curved background the image intensities of the background sphere are stretched relative to the central patch leading to a step change in luminance across the boundary. At the upper boundary the intensity of the patch close to the boundary exceeds that of the background and at the lower boundary the intensity of the patch in the neighbourhood of the boundary is less than that of the adjacent background region. These relationships are reversed in the case of highly curved backgrounds. In the case of a less curved background the presence of a dark region at the upper boundary would be expected to induce a lightening of the top of the central patch and a light region at the lower boundary would be expected to darken the bottom of the central patch. This is similar to the pattern of change in the image intensities that would be produced by an increase in curvature of the central patch. It is possible that such luminance-contrast-induced changes in brightness may be interpreted as the result of a change in curvature by higher order mechanisms. In other words, this may be an example of brightness contrast masquerading as curvature contrast. It should be noted that the exact nature of the luminance discontinuities at the boundary of the central patch depends upon light source position.

In Experiment 2 subjects were presented with the same stimuli as in Experiment 1; but this time each stimulus surface was illuminated face on, rather than from above. The reduction in the effect demonstrates that local contrast-induced changes in brightness contribute to the change in perceived curvature. We next tested for the presence of the effect using stimuli defined by either shading or texture information (Experiment 3). The effect was found to exist under both experimental conditions indicating that three-dimensional curvature contrast can occur in conditions in which there are either no texture cues or no variation in image intensity due to shading.

The results of Experiment 4, in which each inducing surface was replaced with an array of spherical patches, demonstrate that spatial interactions in curvature processing persist when the inducing and test surfaces are separated. We will argue that the results from this experiment constitute evidence that three-dimensional curvature contrast cannot be adequately explained in terms of local luminance-contrast-induced changes in brightness. The results of Experiment 5, in which the surrounding surfaces used in Experiment 4 were replaced with their photographic negatives, demonstrate that the presence of three-dimensional curvature contrast in this type of stimulus configuration cannot be explained in terms of either simultaneous *contrast contrast* effects or lateral influences at the level of the representation of two-dimensional line curvature. We will argue that, taken together, the results from Experiments 2 to 5 suggest that, although changes in perceived brightness and contrast clearly contribute to the effect, there is evidence for an additional contrast effect which acts at the level of the representation of surface curvature.

METHODS

Subjects

Two subjects participated in the experiments. Both subjects had some experience in curvature discrimination tasks. However, one subject, M.F., remained naïve as to the goal of the experiments. Subjects had normal acuity or were corrected for refractive error.

Stimulus generation and display

Stimuli were constructed by ray casting (Foley *et al.*, 1990). The stimulus generation software allowed control over the curvature of the stimuli, their location in the modelling space, the viewpoint and the location of a single point light source for each surface. The surfaces were rendered using a Lambetian illumination model with a small ambient term:

$$P = sI_a + sI_p(\mathbf{N} \cdot \mathbf{L}),$$

where P is the computed brightness, s is the albedo, I_a is the intensity of ambient illumination, and I_p is the intensity of direct illumination. **N** and **L** are the surface normal and light source direction unit vectors.

Texture was added to the spherical surface stimuli using a texture mapping technique. The plane cannot be mapped onto a doubly curved surface without distortion. The nature of the distortion depends upon the mapping function. An equidistant azimuthal mapping, which preserves radial distances, was chosen. A detailed account of this mapping technique is described in earlier papers (Curran & Johnston, 1994b; Johnston & Passmore, 1994a). The advantage of this texture mapping

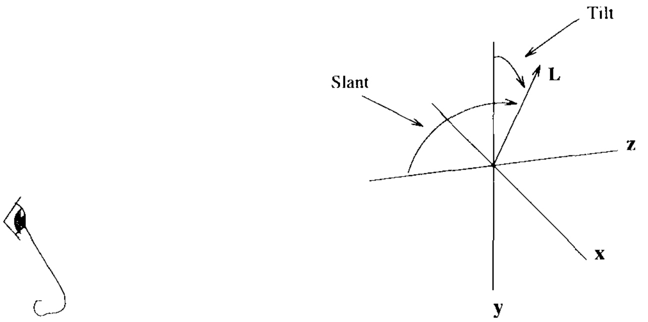

FIGURE 2. Light source slant and tilt as defined in the experiments. With the Cartesian coordinate system centred on the stimulus being viewed, tilt is defined as the angle between the positive y-axis and the projection of the light source vector **L** on the x–y plane. Slant is defined as the angle between the light source vector and the positive z-axis.

technique is that for radial directions there are equal amounts of texture for equal amounts of distance along the surface. In the alternative technique in which the texture is carved from a solid block the size of each texture element depends upon the angle of cut and position relative to the voxels in the solid. In one of the experiments described below texture provides the only cue to curvature; therefore we chose a grey-level checkerboard texture pattern which we know from previous experiments (Curran & Johnston, 1996) provides effective cues to curvature.

Rays were projected from a viewpoint which was 75 cm from the computer screen. The stimuli were displayed on a 19" Sony Trinitron monitor screen under the control of a SUN Sparcstation 330. The grey level display provided 8 bit resolution per pixel. In order to linearize the display a look-up table of luminance values was determined with a micro-photometer and used to control stimulus brightness. This left 166 steps in intensity following linearization. The position and direction of the light source are specified with reference to a coordinate frame centred on the patch. The z-axis extends out from the centre of the patch. Light source tilt is defined as the angle between the projection of the light source vector and the positive y-axis, and light source slant describes the angle of the light source vector relative to the z-axis (see Fig. 2).

EXPERIMENT 1: MEASURING THREE-DIMENSIONAL CURVATURE CONTRAST

In this experiment subjects were presented with stimuli similar to that depicted in Fig. 1. The background spheres were viewed through apertures with radii of 1.46 cm. The apertures bounding the central patches had radii of 0.86 cm. The magnitude of the illusion was measured as a function of the curvature difference of the background spheres, with curvature defined as the reciprocal of the radius. The curvature of the background spheres differed by either 0, 0.12, 0.24 or 0.38 cm^{-1}. Thus the radii of the left and right background spheres varied from 2.1 to 3.5 cm and from 1.5 to 2.1 cm, respectively. All rendered surfaces were illuminated by a point light source positioned 100 cm from the sphere in the direction 60 deg slant, 0 deg tilt. The display was viewed monocularly, from a distance of 75 cm, in a darkened room. Subjects were immobilized with a chin and head rest during a given experimental run; eye movements were not restricted. The curvature difference between the central spherical test patches was varied from trial to trial. On each trial the curvature of both test patches was set with the constraint that the mean curvature of the two patches was equal to the mean curvature of the background spheres. Neither the radii of the test patches nor the background spheres were, at any time, less than the radii of their apertures. It was explained to subjects that they would be viewing pairs of partially occluded computer-generated spheres and that a spherical surface patch would be superimposed on each sphere.

The subjects' task was to indicate, with the press of a button, which of the two central test patches appeared more curved. Johnston and Passmore (1994a) present evidence from a series of experiments that subjects respond on the basis of perceived curvature in tasks of this kind rather than on the basis of luminance-contrast cues. For example they demonstrated that varying the albedo of shaded spherical stimuli over trials, which has no effect on the Michelson contrast of a local surface patch, resulted in elevated curvature discrimination thresholds. Similarly, Curran and Johnston (Curran & Johnston, 1996, 1994a) demonstrate that increasing the tilt of a spherical patch's illuminant causes the surface stimulus to appear less curved, even though stimulus contrast is unchanged.

Note that the test-patch texture was rotated with respect to the surface texture of the background sphere (as shown in Fig. 1), which prevented subjects from responding on the basis of the presence or absence of a texture discontinuity at the point of intersection of the two surfaces. This misalignment of the textures also acted as a segmentation aid, which made the boundaries of the test patches explicit. Changes in perceived curvature were measured using an adaptive method of constant stimuli, APE (Watt & Andrews, 1981). The point of subjective equality (PSE) was defined as the 50% point on the psychometric function, and is a measure of how much the central patches differ in their curvature when they appear equally curved. Subjects generated two psychometric functions for each of the four background "curvature difference" conditions described above.

Results

The results for two subjects are shown in Fig. 3, which plots the curvature difference of the two test patches at the PSE as a function of the difference in curvature of the background spheres. It is clear that the more the background spheres differ in their curvature the greater the curvature difference must be between the central patches in order for them to appear equally curved. The slopes of the lines fit to the data points in Fig. 3 may be considered as a measure of the strength of the illusion—

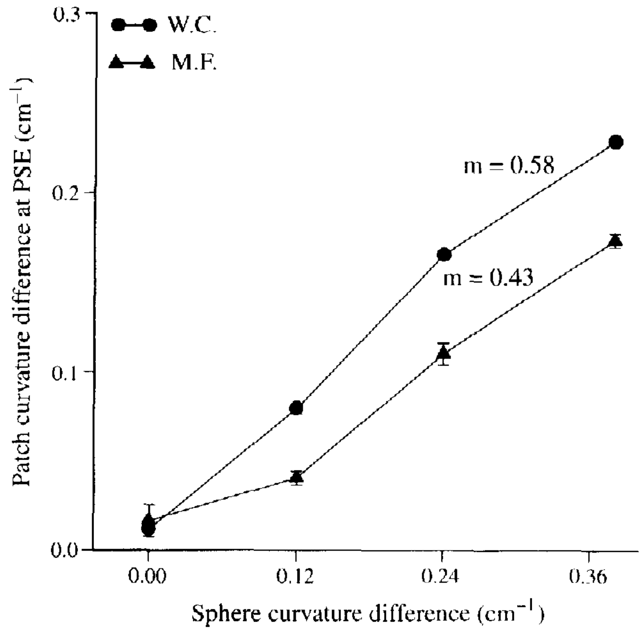

FIGURE 3. The strength of three-dimensional curvature contrast as a function of the difference in curvature between the two background spheres. The ordinate plots the curvature difference between the two central patches when they appeared equally curved. The slope of the functions (0.58 and 0.43 for subjects W.C. and M.F., respectively) may be taken as a measure of the strength of the illusion. In this and subsequent graphs vertical bars represent ± 1 SD.

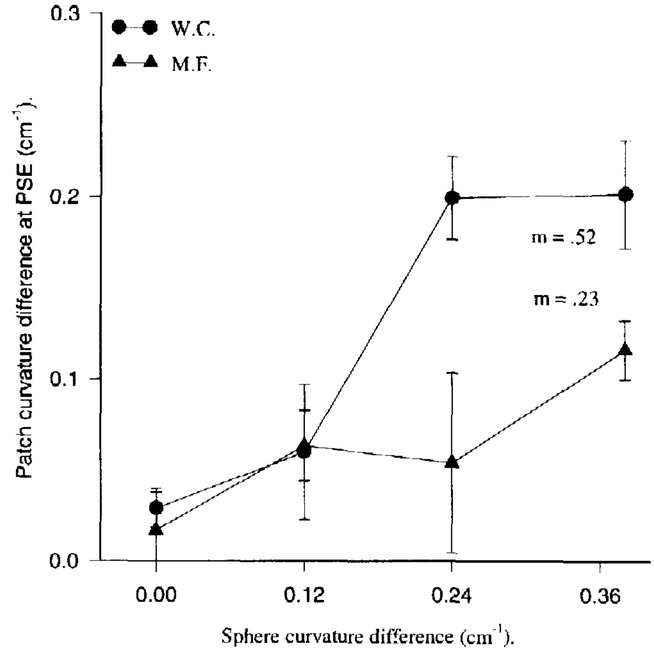

FIGURE 4. The strength of three-dimensional curvature contrast when stimuli are illuminated by a light source perpendicular to the centre of each central patch. Although weakened, as demonstrated by the reduced slopes of the functions relative to Fig. 3, the effect clearly persists under this manipulation.

the steeper the slope, the stronger the illusion. The line fit to the data generated by subject M.F. has a slope of 0.43, and the line fit to W.C.'s data has a slope of 0.58. This corresponds to a shift in perceived curvature equivalent to 21% and 29%, respectively, of the background surface's curvature.

Thus three-dimensional curvature contrast is clearly a strong and readily quantifiable effect. What is not clear, however, is the level of processing at which it occurs. It is possible that the critical spatial interactions may occur at the level of brightness processing (see earlier discussion). An alternative possibility is that they occur after the representation of surface geometry, and in particular after the representation of surface curvature. There is a growing body of evidence that curvature might be computed directly from the information in the retinae rather than from some intermediate description of depth or surface orientation (Johnston & Passmore, 1994a; Rogers & Cagenello, 1989; Stevens, 1992). Johnston and Passmore (1994a, b) used a surface alignment task to measure subjects' curvature and slant discrimination thresholds as a function of light source slant. They reported that, whereas increasing the light source slant resulted in an increase in surface-slant discrimination thresholds, subjects' surface-curvature discrimination thresholds decreased. This differential effect of light source position on slant and curvature discrimination was also found for surfaces viewed stereoscopically (Johnston & Passmore, 1994b). These results are similar to the results of Rogers & Cagenello (1989), who tested subjects' curvature discrimination thresholds for parabolic stimuli presented stereoscopically. It was reported that the disparity range of their displays at curvature discrimination threshold was one-third that required to detect a change in surface slant over the same spatial extent. The dissociation between slant and curvature discrimination thresholds addressed in the above studies is strong evidence that surface curvature does not depend upon the prior encoding of surface orientation. The following two experiments are an attempt to determine whether three-dimensional curvature contrast occurs at the level of brightness representation, or at the level of curvature encoding.

EXPERIMENT 2: CHANGING THE LIGHT SOURCE POSITION

In the previous experiment each surface was illuminated by a light source oriented at 0 deg tilt, 60 deg slant with respect to the line of sight. As pointed out above, it is possible that the differences in apparent curvature between the central patches may have resulted from changes in brightness induced by the surrounding context. Changing the light source position affects the luminance distribution within the patch without changing depicted curvature. If there were no effects of light source position on the curvature contrast effect then low-level luminance-contrast-induced effects on perceived curvature could be ignored. To investigate this possibility the light source was oriented at 0 deg tilt and 0 deg slant. The procedure in Experiment 2 was identical to that used in the first experiment.

Results

Subjects generated two psychometric functions for each background curvature condition. Figure 4 plots the data from both subjects. We can see that, for both subjects, the illusion remains when each surface is rendered with the illuminant oriented normal to the centre of the surface. Change in the strength of the effect may be estimated by comparing the slopes of the lines fit to the data sets in Experiment 2 with those fit to the data from Experiment 1. We can see that for one subject, W.C., the strength of the effect was only slightly weaker in Experiment 2 (slope, $m = 0.52$) than in Experiment 1 ($m = 0.58$). In the case of subject M.F., however, the magnitude of the illusion was effectively halved, with the slope of the lines fit to the data being reduced from 0.43 to 0.23. The observation that the strength of the contrast effect varies with light source position suggests low-level context-induced changes in the apparent brightness contrast of the test patches influence perceived surface curvature from shading. However, we should note that perceived curvature is also influenced by light source position (Curran & Johnston, 1996).

EXPERIMENT 3: THREE-DIMENSIONAL CURVATURE CONTRAST AND SINGLE CUES

In this experiment we tested whether the curvature contrast effect is present when surface stimuli are defined by either shading or texture cues alone. If brightness contrast is the only factor we need to consider in explaining the curvature contrast effect then the effect should persist when the stimuli contain shading information alone, and disappear when stimuli are defined by texture alone.

The curvature values selected for the background spheres were identical to those used in the previous two experiments. Surfaces were illuminated from a light source position identical to that used in Experiment 1. For the condition in which shading was the only curvature cue present, texture was removed by setting the texture contrast to zero. In the case of the "texture-only" condition, shading was removed as a source of curvature information by setting the direct illumination parameter of the shading model, I_p, to zero, and illuminating the surfaces with just the ambient illumination parameter, I_a.

When the curvature of the central patch in the shading-only condition was identical to that of the background sphere on which the patch was superimposed, the central patch could not be visually segmented from the background sphere. Consequently, subjects could not tell when a pair of such patches had appeared. To overcome this problem of identifying when the test stimuli were present, each presentation was accompanied by an audible signal. Furthermore, to overcome the segmentation problem, the boundary between each superimposed patch and background sphere was marked by a thin, 1-pixel wide, dark circle. These presentation and segmentation cues were also implemented in the texture-only condition.

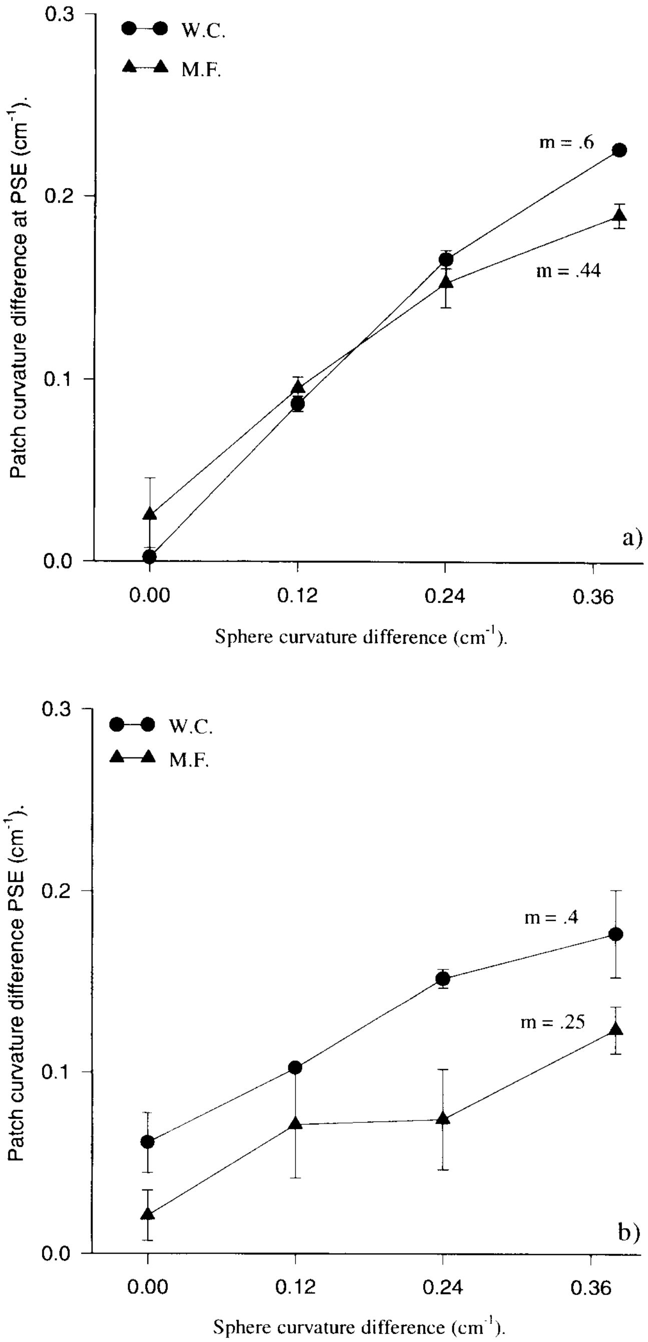

FIGURE 5. The magnitude of three-dimensional curvature contrast as a function of the curvature difference of the inducing spheres when (a) shading or (b) texture was the only curvature cue present in the image. The data demonstrate a persistence of the effect under both conditions, although it was considerably reduced in the "texture-only" condition.

Results

Figure 5(a and b) plots the results from both the shading-only and texture-only conditions. The slopes of the lines fitted to the data sets plotted in Fig. 5(a) demonstrate that the magnitude of the illusion was virtually unaffected when shading was the only curvature

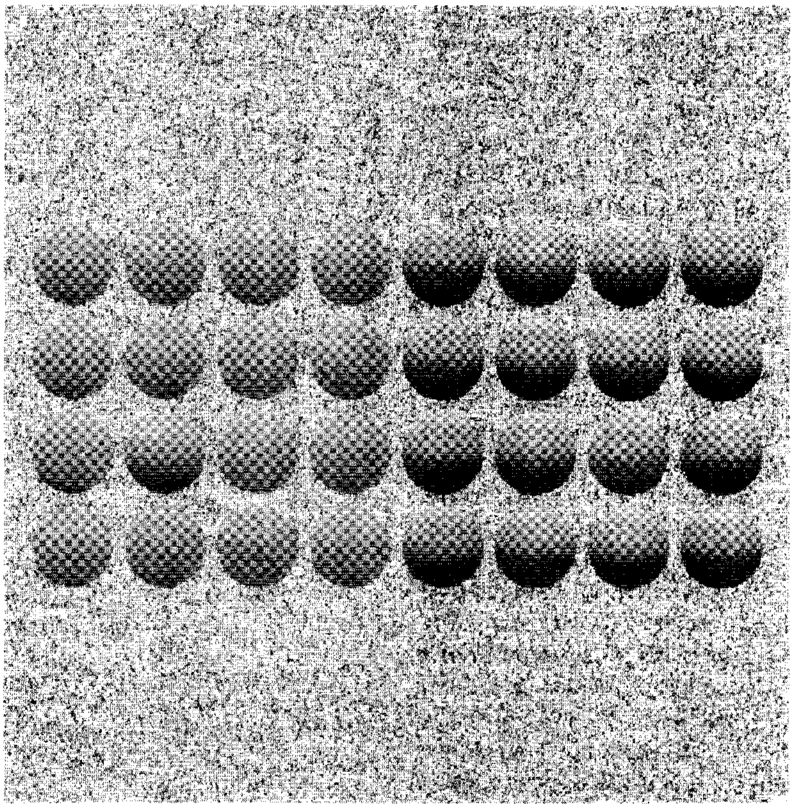

FIGURE 6. An example of the stimuli used in Experiment 4. The background spheres used in the previous experiments were replaced with two arrays of spherical patches that were either more or less curved than the test patches. Subjects were asked to make curvature discrimination judgements between the second and seventh patch in the third row from the top. In the above example the array of surrounding patches on the left have a curvature of 0.5 cm^{-1}, the surrounding patches on the right have a curvature of 1.1 cm^{-1}, and the two test patches have a curvature of 0.81 cm^{-1}.

cue present. The line fit to W.C.'s data has a slope of 0.6, and the line fit to M.F.'s data has a slope of 0.44. These slopes are very similar to those obtained in Experiment 1 (0.58 and 0.43 for W.C. and M.F., respectively). The results from the texture-only condition [Fig. 5(b)] demonstrate that, although somewhat reduced, three-dimensional curvature contrast persisted for both subjects when stimuli were defined by texture alone. This is reflected in the comparatively lower slopes of the lines fit to subjects' data (0.4 and 0.25 for W.C. and M.F., respectively).

The results of Experiment 3 suggest that the effect observed in Experiment 1, in which both cues were present, cannot wholly be explained in terms of brightness contrast interactions. It seems that spatial interactions at some other level also make a contribution to the effect. One possibility is that interactions giving rise to the illusion also occur at the level of the representation of surface curvature. An alternative explanation is that the apparent curvature of the test patches is, in part, a consequence of low-level interactions similar to the two-dimensional line curvature contrast effect reported by Gibson (1933). The checkerboard texture contains line segments whose two-dimensional curvature varies with the curvature of the surface onto which the texture is mapped. It may be that the curvature of such lines in the texture of an inducing surface may shift the apparent curvature of texture edges in the test patches. This, in turn, may influence perceived surface curvature. However, we are not aware of any work showing that the apparent curvature of lines, of mixed sign and variable curvature, can be influenced by a spatial context of assorted curved lines whose mean curvature is different from the test lines. In our next experiment we investigated whether the spatial interactions underlying the changes in perceived curvature occur locally, at the occluding boundary separating the test and inducing surfaces, or whether the effect can be induced over a wider spatial extent.

EXPERIMENT 4: THE SPATIAL EXTENT OF THREE-DIMENSIONAL CURVATURE CONTRAST

In this experiment we replaced each background sphere used in the previous experiments with an array of 15 spherical surface patches (see Fig. 6). Each of these patches was bounded by an aperture equal in size to the apertures bounding the test patches. We used this type of stimulus configuration to investigate whether three-dimensional curvature contrast results from local spatial interactions. If so, we should expect the effect to disappear when the inducing surface is replaced with surfaces spatially separate from the test surfaces. If the effect persists, this would be evidence that the spatial interactions underlying the effect are more global in nature. Further, because the inducing and test stimuli do not overlap, it is clear that one could not invoke an explanation in terms of luminance-contrast-induced local brightness effects. One might consider the possibility of bright or dark patches acting at a distance to induce brightness change, but interactions of this kind would not result in three-dimensional curvature contrast. The reason for this assertion becomes clear when one compares the brightness patterns of Fig. 1 with those of Fig. 6. As pointed out earlier, the contrast in luminance values between the right background sphere and its central patch (see Fig. 1) induces an apparent darkening in the upper region of the patch and an apparent lightening in the lower region of the patch. Suppose this type of interaction also occurred when the inducing and test stimuli were spatially separate, then a reversal of the contrast-induced change in brightness should reverse the illusion. The "surround" patches on the right of Fig. 6 are more curved than the test patches, and the array of patches on the left are less curved than the test patches. The top part of the right hand test patch is close to the darker area of the patch above it. In Fig. 1 this region of the right hand test patch is adjacent to a lighter region of the surrounding sphere. In Fig. 6 the bottom part of the right hand test patch is close to the brighter part of the patch below it, whereas in Fig. 1 it is adjacent to a darker area. Thus we have contrived to produce a reversal of the luminance relationships seen in Fig. 1.

As well as the adoption of arrays of patches, the procedure in Experiment 4 differed from the earlier experiments in a number of ways. The mean curvature of the surround patches was fixed at 0.81 cm^{-1}. Their curvatures differed by either 0, 0.3 or 0.61 cm^{-1}; thus the radii of the spherical patches in the left and right arrays varied from 1.24 to 2 cm and from 0.9 to 1.24 cm, respectively. As in earlier experiments, the curvatures of the two test patches were set with the constraint that their mean curvature was equal to the mean curvature of the surround patches. The inducing and test stimuli were presented against a random grey-level noise background. Subjects were instructed to compare the curvature of the second and seventh spherical patch in the third row of the display. The surround patches remained on the monitor throughout the experiment; the test stimuli were replaced with a random grey-level noise pattern between presentations, thus making explicit to subjects the spatial location of the patches being compared. Four psychometric functions per subject were obtained for each of the three curvature-difference conditions.

Results

The results for both subjects are plotted in Fig. 7. It is apparent from these results that, despite the introduction of a spatial separation between inducing and test surfaces, a change in the curvature of the surround patches continued to have a measurable effect on the perceived curvature of the test patches. However, the magnitude of the effect was substantially reduced for both subjects. This is reflected in the slopes of the lines fit to each set of data (0.13 and 0.11 for subjects W.C. and M.F., respectively). Note that the effect is in the same direction as in the earlier experiments. That is, when both test patches are of equal curvature, as in Fig. 6, the left test patch appears more curved than the right test patch.

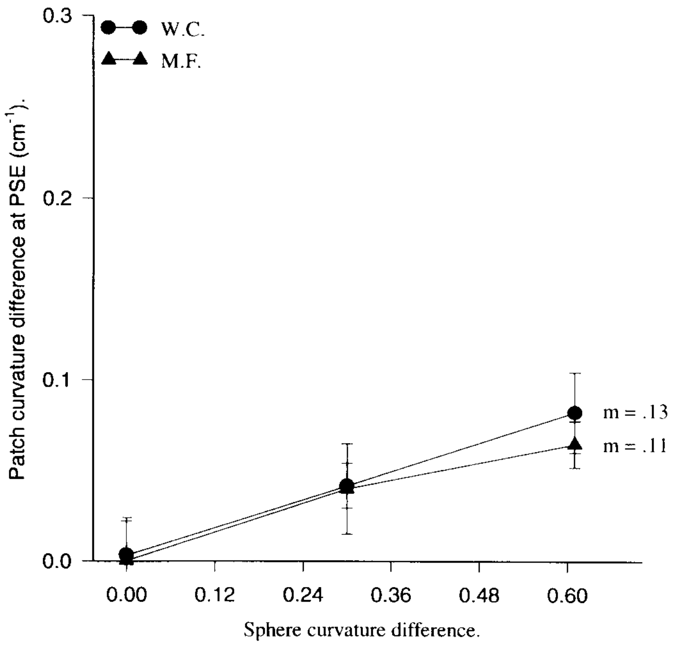

FIGURE 7. A measure of the magnitude of three-dimensional curvature contrast as a function of the curvature difference between the inducing arrays. Although substantially weakened, there is still a measurable effect.

The results from Experiment 4 demonstrate that the spatial interactions underlying three-dimensional curvature contrast are not restricted to local regions of the image; rather, we have found that the apparent curvature of a rendered surface continues to be influenced when the inducing stimuli are spatially separate from the test stimuli. This is consistent with earlier reports of depth-from-disparity contrast effects (Kumar & Glasner, 1991), in which the disparity of remote objects (up to 25 deg away from fixation) was found to influence perceived differences in the depths of items near fixation.

The persistence of three-dimensional curvature contrast under the conditions of Experiment 4 cannot be explained in terms of local luminance-induced contrast effects. The stimulus configuration used in this experiment isolates the test and inducing patches and reverses the luminance relationships present in Experiment 1 (see discussion, above). If three-dimensional curvature contrast were reducible to luminance-contrast-induced changes in brightness alone, one would expect the effect to reverse under these conditions. However, the effect was in the same direction as in earlier experiments; suggesting that an explanation based on interactions at the level of brightness encoding is insufficient.

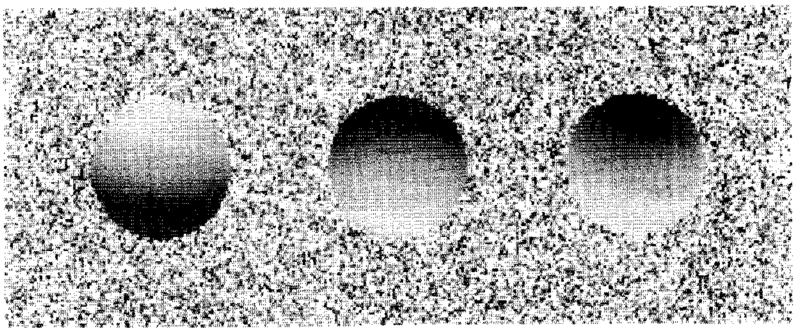

FIGURE 8. The left stimulus depicts a spherical patch with a curvature of 1.1 cm^{-1}. The centre stimulus depicts the same spherical patch illuminated from below, and the stimulus on the right is a photographic negative of the left-hand stimulus. The image has been enlarged for ease of comparing the intensity gradients of the centre and right-hand stimuli. It is clear from a comparison of these stimuli that replacing the left-hand patch with its photographic negative is not equivalent to reversing its illuminant direction.

Although changes in perceived brightness cannot explain the persistence of three-dimensional curvature contrast under the conditions of Experiment 4, the results would be consistent with the presence of a simultaneous *contrast contrast* effect. Simultaneous contrast contrast, a term coined by Heeger and Robison (1994), describes how the apparent contrast of a test stimulus is partly determined by the contrast of the surround. The phenomenon was measured by Chubb *et al.* (1989), who reported that the perceived contrast of a patch of random texture varied inversely with the contrast of surrounding texture. The effect was reported to be dependent on the relative spatial frequencies of the background and test textures, with the data suggesting that induced contrast change has approximately a 1-octave spatial-frequency bandwidth. Simultaneous contrast contrast has also been reported for other types of stimuli, including gratings (Cannon & Fullenkamp, 1991, 1993; Solomon *et al.*, 1990) and Gabor patches (Cannon & Fullenkamp, 1994). The magnitude of three-dimensional curvature contrast was shown to be reduced with spatial separation in Experiment 4; similarly, simultaneous contrast contrast has been shown to be inversely related to the spatial separation of the inducing surround and the central test area (Cannon & Fullenkamp, 1991). Cannon and Fullenkamp (1994) also report that the apparent contrast of a central Gabor patch is inhibited when the test patch is flanked by two peripheral Gabor patches with double the contrast.

Increasing the curvature of a spherical patch has the effect of increasing the brightness range and contrast of the patch. This raises the question whether the presence of three-dimensional curvature contrast in Experiment 4 was a consequence of simultaneous contrast contrast effects in the stimulus display. We also cannot ignore the possibility discussed earlier, that the effect may be a consequence of two-dimensional line curvature interactions arising in the processing of the image texture present in the inducing and test regions. Our final experiment addresses both these issues.

EXPERIMENT 5: PHOTOGRAPHIC NEGATIVES

In this experiment the test stimuli were surrounded either by arrays of spherical patches, as in Experiment 4, or by their photographic negatives (see Fig. 8). The photographic negative of each surrounding patch was generated by inverting the image luminance values about the patch's mean luminance. This manipulation does not change brightness contrast, but it does radically disrupt the surface curvature cue (Cavanagh & Leclerc, 1989; Johnston, 1992; Johnston & Passmore, 1994a). If three-dimensional curvature contrast can be explained in terms of simultaneous contrast contrast effects, then the illusion should be just as compelling whether the test patches are surrounded by arrays of spherical surface patches or by their photographic negatives. If, on the other hand the effect can be reduced to curvature interactions, we would expect three-dimensional curvature contrast to persist in the former condition, but to be substantially weakened or abolished when the surrounding arrays are photographic negatives.

As in Experiment 4, the test patches were defined by shading and texture cues. However, in contrast to Experiment 4 the stimuli in the surrounding arrays were defined by shading information alone. As pointed out above, the surrounding arrays were either rendered images of curved surfaces or their photographic negatives. The curvature differences between background stimuli were identical to Experiment 4. Each subject generated four psychometric functions for each of the three curvature-difference conditions.

Results

Figure 9 (a and b) plot the results for subjects W.C. and M.F., respectively. The solid triangles plot the results of the "curvature" condition, in which the test patches were surrounded by arrays of curved surfaces; the solid squares plot the results of the "negatives" condition, in which the background arrays of curved surfaces were replaced with their photographic negatives. In the absence of three-dimensional curvature contrast subjects' data would lie

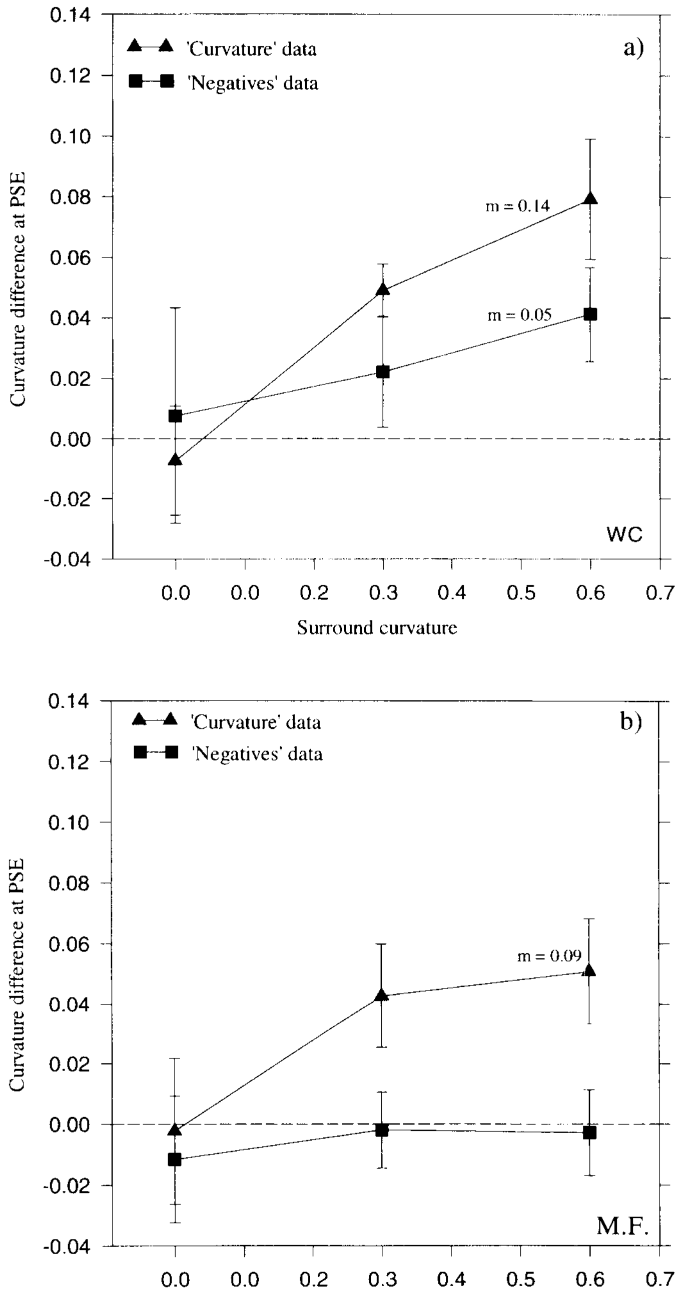

FIGURE 9. The data from Experiment 5, in which the presence of three-dimensional curvature contrast was tested for background arrays containing either spherical patches (▲) or their photographic negatives (■). The data plot three-dimensional curvature contrast as a function of the curvature difference between the background arrays. The data show that the effect persisted in the "curvature" condition. However, in the "photographic negative" condition it was reduced by *ca* 60% for one subject (W.C.) and completely abolished for the second subject (M.F.).

on the broken line in Fig. 9. It can be seen from the data that, as would be expected on the basis of Experiment 4, the effect persisted for both subjects when the surrounding arrays were curved surfaces. Its magnitude is similar to that recorded in Experiment 4. The data sets have slopes of 0.14 and 0.09 for W.C. and M.F., respectively. However, when these arrays were replaced with their photographic negatives, the effect was completely abolished for subject M.F. and reduced by 60% for subject W.C. (slope = 0.05). Because brightness contrast was identical for both conditions, one would expect the curvature illusion to be equally strong in both conditions if it were reducible to simultaneous contrast contrast. However, given that it was absent for one subject and substantially weakened for the other, we can conclude that the presence of three-dimensional curvature contrast in Experiment 4 was not driven by simultaneous contrast contrast effects.

DISCUSSION

We have described our investigations of a context effect, in which the apparent curvature of a spherical patch can be changed by placing the patch in the vicinity of another surface (or several surfaces) of a different curvature. The results of Experiment 1 demonstrate that three-dimensional curvature contrast is a strong and quantifiable effect. The magnitude of the illusion can be characterized by means of a percentage measurement of the background surface's curvature. Using this metric, we found that the shift in the apparent curvature of a test patch was around 25% of the inducing surface's curvature. In Experiment 2 we illuminated surfaces face on, a manipulation which affects the intensity distribution within the stimuli without affecting depicted curvature. This resulted in a reduction in the effect, suggesting that low level context-induced changes in the apparent brightness contrast of the test patches contribute to the change in perceived curvature. The results of Experiment 3, in which three-dimensional curvature contrast was measured using surfaces defined by either shading or texture cues, can also be interpreted in this way. However, the fact that the effect was present in displays of stimuli containing texture cues alone suggests that three-dimensional curvature contrast cannot be fully accounted for by interactions at the level of brightness encoding. This is further supported by the finding that the effect persisted when the brightness pattern in the stimulus display was reversed by replacing each background sphere with an array of spherical patches (Experiment 4). The results of experiments four and five could not be explained in terms of simultaneous contrast contrast effects suggesting that the curvature contrast effect is, at least in part, the result of a comparison process acting at the level of the encoding and representation of surface curvature.

One could argue that the contrast effects described here might be sufficiently explained by low-level or two-dimensional induction effects without invoking processes involved in the representation of surface structure, and that it is perhaps premature to suggest interactions at the level of the representation of surface curvature are involved. Subjects report making judgements about the apparent shape of the surface patches but it may be that these changes in perceived shape are secondary effects resulting from changes in the perception of two-dimensional image properties which could act as data for mechanisms encoding depth or shape. One could consider a two-dimensional line curvature contrast effect similar to that described by Gibson (1933). Gibson reported that, when presented alongside a background of curved lines, a straight line appears slightly curved and that its apparent curvature is of the opposite polarity to the background lines. The checkerboard texture used in our experiments contains salient edges. It is possible that the perceived two-dimensional curvature of edges in the background stimuli influence the curvature of edges in the test patches, which could, in turn, lead to a change in apparent surface curvature. However, we are not aware of any work showing that curved lines appear less curved when flanked by lines of a higher curvature, and vice versa, when the inducing and test lines differ in their orientation, which is the situation in the experiments described here (texture orientation for the test and inducing stimuli differed by 30 deg). In addition, in these experiments the two-dimensional curvature of texture edges vary in sign and in magnitude across the surfaces.

We also considered the role of luminance contrast domain effects in some detail. Here one might argue that it is changes in perceived brightness or a change of brightness contrast in the test patch that leads to changes in perceived curvature. Indeed, the curvature contrast effect was reduced for a light source direction which resulted in a lower luminance contrast in the test patches and we have demonstrated in an earlier paper (Curran & Johnston, 1994a, 1996) that perceived curvature decreases with light source slant. However, there is no simple relationship between luminance contrast and perceived curvature. Perceived curvature varies with light source tilt, a manipulation which does not affect contrast (Curran & Johnston, 1996). Further, curvature discrimination thresholds are unaffected by adding stimulus noise in the form of a random variation in contrast over trials, although this manipulation does increase thresholds for an analogous task utilizing photographic negatives of shaded curved patches (Johnston & Passmore, 1994a). It would appear from the experiments described above that changes in perceived brightness can influence perceived curvature. However, it should be noted that there are a number of examples which run counter to the idea of a sequential dependency of three-dimensional shape processing on brightness computation, the Mach card being the most widely cited, in which changes in perceived geometry lead to changes in perceived brightness (Adelson, 1993; Knill & Kersten, 1991). A more cautious conclusion would be that the computations involved in the perception of brightness and surface geometry are mutually dependent and are a result of interpreting the image in relation to possible causal influences in the scene.

Given the possibility that the curvature contrast effect might be influenced by two-dimensional image based induction effects of the kind described above we also need to consider whether subjects might match the test patches on the basis of two-dimensional appearance rather than apparent solid shape. Although subjects reported that they made their judgments on the basis of perceived solid shape, it is not possible to completely discount the proposal that physically different patches may appear identical as a result of two-dimensional induced changes on the basis of the experiments described here. However, there is evidence that subjects base their judgments on perceived solid shape in tasks of this kind. In the present experiments shading and texture cues define a particular curved surface patch with a specified curvature, but it is possible to construct an image in which shading and texture cues are referred to two surfaces with different curvatures. This is equivalent to painting the texture appropriate for one curved surface onto a surface of a different curvature. The weight given to shading and texture cues can then be estimated using perturbation analysis (Maloney & Landy, 1989). In experiments of this type subjects are asked to match the perceived curvature of surface patches defined by consonant shading and texture cues to surface patches defined by incongruent shading and texture cues (Curran & Johnston, 1994b). Subjects make matches based on the apparent curvature of two stimuli which are physically different and which do not necessarily have the same two-dimensional appearance. In addition, Johnston and Passmore (1994) have shown that curvature discrimination thresholds are little affected by variation in the ambient illumination, a manipulation that changes the contrast of shaded patches from trial to trial. This manipulation did, however, increase thresholds for a control condition in which the stimuli were replaced with photographic negatives. This again supports the idea that subjects are making judgements about surface shape in the kind of task decribed here.

We have shown that perceived curvature of a surface patch can be affected by the presence of a context depicting surfaces of a higher or lower curvature in a variety of stimulus configurations. It is possible that in each case the effect results from a different two-dimensional contrast induced change which is specific to that configuration. However, none of these specific explanations could apply to all configurations in which we find a curvature contrast effect. A more parsimonious explanation would be that there is some direct influence of the curvature of patches in the surrounding context on the perceived curvature of the test patch. In particular it is difficult to account for three-dimensional curvature contrast in the array configuration on the basis of simple two-dimensional interactions.

Ramachandran (1988) used arrays of spherical patches to good effect, demonstrating that patches of opposite curvature were readily segregated, and that reversals of perceived curvature with changes in light source orientation occurred *en masse*. This suggested that local interpretations of shape-from-shading are influenced by global factors. The most likely reason for global effects in arrays of shaded patches is an assumption by the visual system that the scene is illuminated from a single direction. For a single patch the pattern of shading does not uniquely determine the local shape of the surface (Erens *et al.*, 1993) if the direction of illumination is unknown. In addition, for single patches, perceived curvature depends upon light source position (Curran & Johnston, 1996). Hence, in the case of a single surface patch, shading provides an ambiguous cue to shape and curvature. Curvature contrast would appear to indicate that perceived curvature of convex surface patches is influenced by comparisons between like neighbours. For arrays of shaded patches of the same sign the visual system can exploit these comparisons between the patches in the following way. Assume the direction of the illumination is invariant with spatial position in the scene. It should be possible to discount the influence of global changes in the direction of illumination on perceived surface curvature by encoding relative curvature, since the effects of illumination direction on perceived curvature should be consistent for all patches in the scene. The implication of this is that the perception of curvature differences should be more robust than the perception of absolute curvature (Johnston & Passmore, 1994a).

An additional reason for encoding relative curvature concerns the problem of object constancy (Johnston, 1992). One of the disadvantages of a curvature description is that it varies with scale; a golf ball is more curved than a soccer ball. It would be useful therefore to describe the surfaces of objects in terms of relative curvature since this measure remains invariant under changes in scale (Koenderink & van Doorn, 1992). The contrast effect described here would have the advantage of highlighting discontinuities in curvature, curvature change and differences in curvature at various points on an object.

To conclude, our investigations suggest that three-dimensional curvature contrast involves interactions at the level of the representation of both brightness and surface curvature. Given that differences in surface geometry appear to give rise to simultaneous contrast effects, we might expect analogous effects in other domains. Indeed, a similar effect has been demonstrated (B. Rogers, personal communication) using surfaces defined by stereoscopic information alone, in which curvature of opposite sign is induced in a fronto-parallel bar by curved flanking bars.

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